WIND TUNNEL INVESTIGATION OF THE AERODYNAMIC INTERACTIONS BETWEEN HELICOPTERS AND TILTROTORS IN A SHIPBOARD ENVIRONMENT

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ABSTRACT

The design and execution of a small-scale wind tunnel investigation of V-22 shipboard interactional aerodynamic phenomena is described. The objectives of the investigation were to quantify the aerodynamic disturbances driving the uncommanded roll response experienced by a ground turning V-22 on the deck of an amphibious ship during recovery operations of upwind rotorcraft. Over 100 hours of wind-on testing were conducted in the US Army 7x10 Wind Tunnel at NASA Ames Research Center, between October 2001 and April 2002. Major model hardware included the fabrication of 1/48-scale representation of an LHA class ship, as well as 1/48-scale powered models of the on-deck V-22 and three upwind aircraft representing a CH-46, a CH-53, and a second V-22. Principal measurements acquired include Particle Image Velocimetry measurements of the flow field and force and moment measurements of the on-deck V-22 response. An overview of the test approach and execution and a general discussion of the results obtained are presented.

NOTATION

A	rotor disk area, πR^2
b	V-22 rotor-rotor distance
C_T	aircraft thrust coefficient, aircraft thrust/$\rho n A V_{tip}^2$
n	number of rotors
Nr	% nominal rotor rotational speed
R	rotor radius
RM	aircraft rolling moment, positive right wing down
Spot	landing spot designation on flightdeck
v_i	hover induced velocity, $V_{tip}\sqrt{C_T/2}$
V_{tip}	blade tip speed, ΩR
WHOD	wheel-height-over-deck
WOD	relative wind over deck expressed as an azimuth (0 deg. down the bow) and magnitude in knots
μ	advance ratio, tunnel speed/Vtip
Ω	rotor rotational speed
ρ	air density

INTRODUCTION

During shipboard compatibility trials conducted in January and August of 1999, the V-22 aircraft on two occasions experienced an uncommanded roll in response to a CH-46 landing two to three spots upwind of the V-22. A video camera covering flightdeck operations on the USS Saipan LHA-2 during the 30-Jan-1999 event provided the frame shown in Figure 1, taken at the point of maximum V-22 roll (5.8 degrees). At the time the V-22 was ground turning at 88% Nr on Spot 8 while a CH-46 (estimated at 18,500 lbs. gross weight) was being recovered at Spot 6, approximately 255 feet upwind of the V-22. Relative wind-over-deck (WOD) was recorded as 357 deg. at 38 knots. Because of its potentially negative impact on shipboard operations and safety, the V-22 uncommanded roll in response to the approach of an upwind aircraft was classified as a deficiency requiring correction prior to operational deployment.

To successfully resolve what became known as the V-22 "Roll On-Deck" (ROD) problem, the V-22 Integrated Test Team (ITT) launched a comprehensive multi-phase program composed of math model development and validation efforts in parallel with full-scale ground-based and shipboard interaction testing designed to gather the

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engineering data in build-up fashion which ultimately led to the design, implementation, and demonstration of a fix. In August of 2001 (before the V-22 had returned to flight status), it was decided that a wind tunnel test, if performed in a timely manner, could provide valuable insights into the aerodynamic interaction mechanisms involved and perhaps help identify the worst-case uncommanded roll scenarios before the V-22 returned to sea trials. This paper describes the resulting joint NAVAIR/Army/NASA wind tunnel investigation of V-22 shipboard interactional aerodynamic phenomena sponsored by the V-22 Program Office.

Figure 1. "Roll On-deck" event aboard USS Saipan LHA-2, 30-Jan-99

WIND TUNNEL TEST REQUIREMENTS

The objectives of a wind tunnel investigation of V-22 shipboard interactional aerodynamic phenomena were stated as follows:

- Quantify the flow field disturbance generated by the upwind rotorcraft and ship combined wake for various rotorcraft operating upstream of a V-22 on-deck of the LHA for use in an analytical study of the aircraft dynamic response.

- Identify critical combinations of upwind aircraft downwash, proximity, and WOD conditions based on measured thrust asymmetry and/or rolling moment response.

The challenge of investigating V-22 ROD interactional aerodynamics in a wind tunnel was to model the contributors (ship, WOD, upstream aircraft, on-deck V-22) with sufficient fidelity to duplicate the governing flow field phenomena, i.e. rotor/wake interactions coupled with the ship airwake environment. For a reasonable reproduction of the full-scale event, the principal similarity parameter that needed to be observed is the ratio of rotor-induced velocity to free stream velocity. This placed little constraint on model scale as long as the nondimensional thrust coefficient and advance ratio of the full-scale rotors

were matched. Fidelity of the airframe representation was secondary at the low speeds being considered.

Minimal model scale was driven more by the packaging of instrumentation and rotor controls. At a minimum, a measurement of roll moment response of the on-deck V-22 was required. Individual rotor thrust measurement was desired to resolve the thrust asymmetry. Although articulated rotors (to reduce hub moment contributions) were desired, variable collective pitch to set thrust at a given RPM was a requirement; cyclic pitch was secondary. Model installation requirements included the ability to yaw the ship in the tunnel test section to simulate portside winds (conditions that are likely to convey approaching aircraft wakes towards the "on-deck" V-22) and variable positioning of the upwind aircraft relative to the ship and on-deck V-22 with minimal flow interference. Control of upwind aircraft thrust and, in some cases, moment trim was also required. In addition to measuring the V-22 rolling moment response, the flow field disturbance itself needed to be quantified. Of particular interest is the vertical velocity field in the plane of the on-deck V-22 rotors.

APPROACH

Given the above requirements and the near-term need for data, the decision was made to conduct a 1/48th-scale test in the Army 7 x 10 Foot Wind Tunnel at NASA Ames Research Center under the direction of the Army/NASA Rotorcraft Division and NAVAIR. Designated as the V-22/Ship/ Helicopter Aerodynamic Interaction Phenomena (VSHAIP) investigation [1], the test was a logical extension of the tiltrotor aeromechanics work being conducted at Ames [2] and the ship airwake work being conducted at NAVAIR [3]. The effort leveraged heavily on NASA investigations of Tiltrotor Descent Aerodynamics using low-cost, small-scale (1/40th) dual rotor models built from off-the-shelf radio-control (RC) model components [4]. Conducting the test at Ames also capitalized on the resident expertise in Particle Image Velocimetry (PIV) [5], an essential element for acquiring the upwind aircraft downwash velocity field.

The primary driver for the model scale selection was the economy and efficiency of conducting the test in the Army 7 x 10 Foot Wind Tunnel. The 1/48th scale satisfied the model fidelity requirements while providing adequate real estate for essential instrumentation. A 1/48th-scale LHA, at roughly 17 ft in length and 4 ft^2 in cross-section, was just about the largest size that could be tested in the 7x10 Foot Wind Tunnel without introducing significant blockage effects at yaw angles up to 15 degrees. In addition, the choice of 1/48th-scale allowed the use of

commercially available plastic model rotorcraft kits for assembling airframe components.

Tunnel and aircraft operating conditions were selected to match nondimensional parameters of rotor thrust coefficient and advance ratio of the full-scale ROD scenario. Rotor tip speed was limited to 33% of full-scale for each aircraft due to the performance of the electric motors powering each aircraft; therefore, tunnel speed was set to match 1/3 full-scale wind speeds. The airwake of the isolated LHA is expected to be independent of Reynolds Number since the sharp leading edges of the ship fix the location of flow separation. Hence, the interaction of the ship wake and rotor wake at 1/48th-scale was assumed an adequate simulation of full-scale events. For this test, yaw angles up to 15 deg (port-side winds) and tunnel speeds up to approximately 33 ft/s were tested. No attempt was made to simulate the atmospheric boundary layer, primarily because of the difficulty in modeling the boundary layer for non-zero ship yaw angles.

Figure 2 shows the installation of the LHA, on-deck V-22, and the CH-46 in the 7x10 Foot Wind Tunnel employed to investigate the V-22 ROD scenario. The ship is mounted to the tunnel turntable to facilitate testing at different relative wind azimuths. The V-22 model is mounted on the ship in a position replicating that of an on-deck V-22 spotted on either deck Spot 7 or deck Spot 8. The upwind aircraft is mounted on a sting extending from the tunnel traverse mechanism to allow positioning of the model relative to the on-deck V-22 in three directions. No attempt was made to model a dynamically translating upwind aircraft; instead, a quasi-steady approach was adopted, taking data with the upwind aircraft held at a number fixed positions along its trajectory. The test objectives were met by acquiring both PIV measurements of the flowfield and force and moment measurements of the on-deck V-22 response over a wide range of upwind aircraft position and WOD conditions.

Figure 2. VSHAIP installation in the Army 7x10Foot Wind Tunnel at NASA Ames

DESCRIPTION OF FACILITY, MODELS, AND MEASUREMENT SYSTEMS

Facility

The 7x10 Foot Wind Tunnel is a closed circuit wind tunnel operated by the U.S. Army Aeroflightdynamics Directorate at NASA Ames Research Center. The constant cross-section test section measures 7-ft high by 10-ft wide by 15-ft long. The tunnel has a 14:1 contraction ratio and a maximum speed of approximately 355 ft/s. The test section turntable is capable of yaw angles up to 360 degrees. An air exchange system allows up to 29.3% air exchange. Since target speeds for this experiment ranged from 13 to 26 ft/s, the tunnel was run with 0% air exchange to eliminate atmospheric influence on the test section flow steadiness. A traverse system, installed in the test section, is capable of traversing in the vertical, lateral, and streamwise directions.

1/48 Scale Models

Most of the model hardware for this test was designed and fabricated by NASA Ames. In order to minimize design and fabrication costs, some compromises were made on the ship and aircraft geometry, none of which were expected to affect the gross aerodynamics of the ship or aircraft. A brief description of the ship and powered aircraft models follows. Details of model design, design trade-offs, and construction are reported in [6].

Ship Model

The ship is a low fidelity, 1/48th scale model of the LHA-2 Saipan amphibious assault ship (Figure 3). At 1/48th-scale the LHA flight deck scales to roughly 200 inches (16.7 ft) in length and 30 inches in width. The model replicates the above waterline portion of the LHA using the same low-fidelity level of detail as the LHA geometry used in recent CFD ship airwake studies for the Joint Ship Helicopter Integration Process (JSHIP) Program [7].

Figure 3. USS Saipan LHA-2

The ship is mounted internally to an aluminum rail that extends nearly the entire length of the ship. The rail is mounted to linear bearings that are welded to the tunnel turntable. The linear bearings allow the ship to be translated longitudinally in the tunnel while the turntable provides the yaw degree of freedom. The LHA was installed off-axis in the test section to favor modeling upwind aircraft approaches to landing spots on the port side of the ship for ship yaw angles of 0 to 15 deg. (portside winds). Figure 4 shows the ship mounted in the wind tunnel while Figure 5 shows the general dimensions of the flightdeck along with the locations of the landing spots.

Figure 4. 1/48-scale LHA installed in Army 7x10 Foot Wind Tunnel
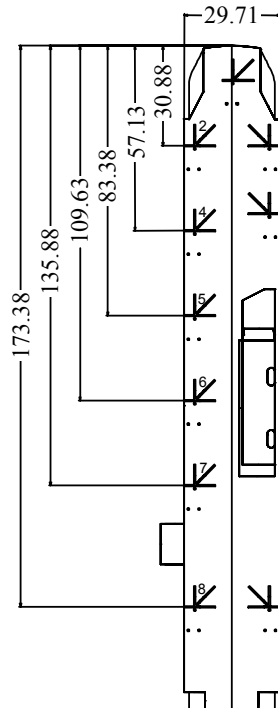
Figure 5. 1/48-scale LHA flightdeck layout (in)

Aircraft Models

Figure 6 shows the four powered rotorcraft models fabricated for the test, representing 3 configurations of rotorcraft: a V-22 tiltrotor, a CH-46 tandem-rotor helicopter, and a CH-53E single-main-rotor helicopter. The primary modeling parameters were rotor diameter, solidity, rotor-rotor position and relative tip speed. Pertinent properties of the scale model aircraft are tabulated in Table 1.
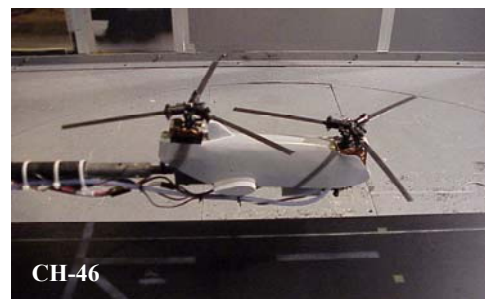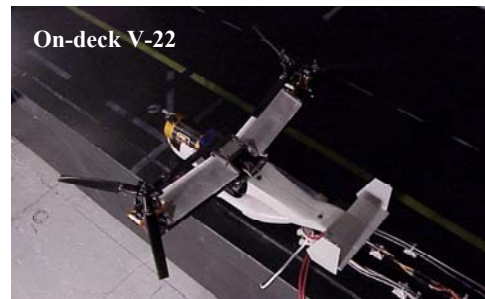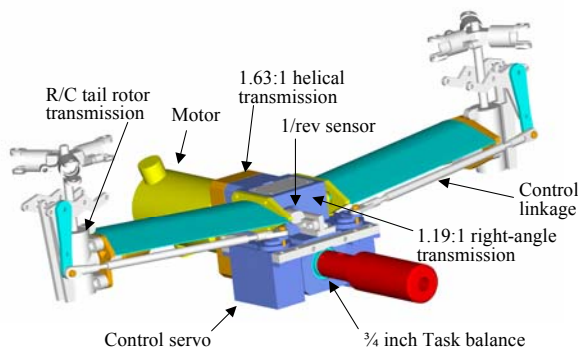

On-deck V-22

CH-46

CH-53E

V-22

Figure 6. 1/48-scale powered rotorcraft models

Table 1. Model Aircraft Properties

	V-22	CH-46	CH-53E
No. of rotors	2	2	1
No. blades per rotor	3	3	5
Rotor radius (in)	4.687	6.311	10.220
Target rotor RPM	6,355	4,224	2,831
Target tip speed (ft/s)	260	233	252
Target tip Reynolds No.	61,616	46,366	114,604
Target thrust coefficient	0.0008[a]	0.0048	0.0108
Motor design speed (rpm)	12,313	4,224	11,324
Gear ratio	1.9375	1.0	4.0
Design power, 125% (W)	251	69	304

[a]on-deck V-22

Figure 7 shows the major components of the tiltrotor model. Rotor dynamic components were built from commercially available radio-control (RC) model components where possible. All of the models used rigid hubs, and had collective control only, no cyclic. Any hub moments generated at the low advance ratios tested were negligible compared to the rotor wake interactions. The rotor blades were fabricated by a RC model propeller manufacturer. In the case of the CH-46 and CH-53E rotor blades, a special low Reynolds Number airfoil was employed to ensure adequate lift could be generated to meet upwind aircraft thrust targets. Custom compact and lightweight model drive systems were designed and built for each model configuration. Each aircraft used a single, high-power density RC model motor mounted within the aircraft to power the rotors. The power available in a motor meeting the dimensional constraints led to the design trade-off of operating at 33% full-scale rotor tip-speed.

Figure 7. Major components of tiltrotor model

Measurement Systems

Aircraft Force and Moment Measurement

The upwind aircraft and the on-deck V-22 were each mounted on a 6-component (5 forces, 1 moment), 0.75-inch internal Task balance functioning as a total loads balance. Airframe contributions to normal force and rolling moment, the components of principal concern for trimming upwind aircraft and quantifying the on-deck V-22 response, were assumed to be negligible compared to rotor contributions. The 1/48th-scale precluded practical implementation of individual rotor thrust measurement on the V-22 model. However, if one assumes that the rotors are the chief contributors to both normal force and rolling moment, individual left and right rotor thrust can be resolved from the total loads balance output.

A LabView based data acquisition system was used to monitor and record output from both the on-deck and upwind aircraft balances. Dynamic force and moment data were recorded at 2048 samples per second over an 8 second window for each test point. All results presented herein represent mean values.

Particle Image Velocimetry

Meeting the principal test objective of quantifying the combined flow field disturbance generated by the upwind rotorcraft and ship wakes for the matrix of scenarios of interest was accomplished employing the Particle Image Velocimetry (PIV) technique. No other flow measurement technique has proven to be as efficient for acquiring concurrent 3-component velocity measurements over relatively large flowfields. In the present case, the area of interest extended from the starboard edge of the LHA flightdeck to four V-22 wingspans off the port deck edge in width ($\approx$ 76 in) and from the flight deck level to a WHOD of 120 ft in height ($\approx$ 30 in) to allow capture of the ship airwake features as well as the wake of the upwind aircraft on approach for landing.

Figure 8 shows a schematic of the PIV setup employed for this test, with the laser and laser light sheet (LLS) optics located on the starboard side of the test section and the cameras on the other. The size chosen for the PIV survey region was 6 ft wide by 3 ft high, centered in the test section. Since velocity data in a cross-flow plane were desired at different streamwise locations corresponding to portside landing spots on the LHA, the LHA was designed to translate longitudinally in the wind tunnel test section to minimize movement (and recalibration) of the PIV optics. Only two PIV set-ups were ultimately used for all four test phases: 1) an upstream set-up to acquire isolated ship airwake measurements at Landing Spots 2 and 4; and 2) a downstream set-up to acquire isolated ship airwake measurements at Landing Spots 7 and 8, isolated V-22

wake measurements, and combined ship/CH-46 wake measurements.

Since the velocity field of interest is that which would be seen by the on-deck V-22, PIV measurements at a given deck spot were acquired in a cross-flow plane that would pass through the V-22 rotor axes, an offset of 4.53 inches aft from the deck spot nose wheel reference point. For expedience, the PIV set-up was designed such that the LLS remained in the cross-flow plane. Consequently, when the ship is yawed in the test section, the LLS is no longer perpendicular to the longitudinal axis of the ship. This trade-off results in an oblique survey region as shown in Figure 9.

For the present test a PIV acquisition rate of 2 Hz was employed. No attempt was made to synchronize the image acquisition with the rotor rotational speed since the objective of the PIV measurements was the mean velocity field. PIV images presented herein represent an average of 50 to 100 individual frames. Additional details regarding the PIV setup and a presentation of select velocity fields are provided in [8].
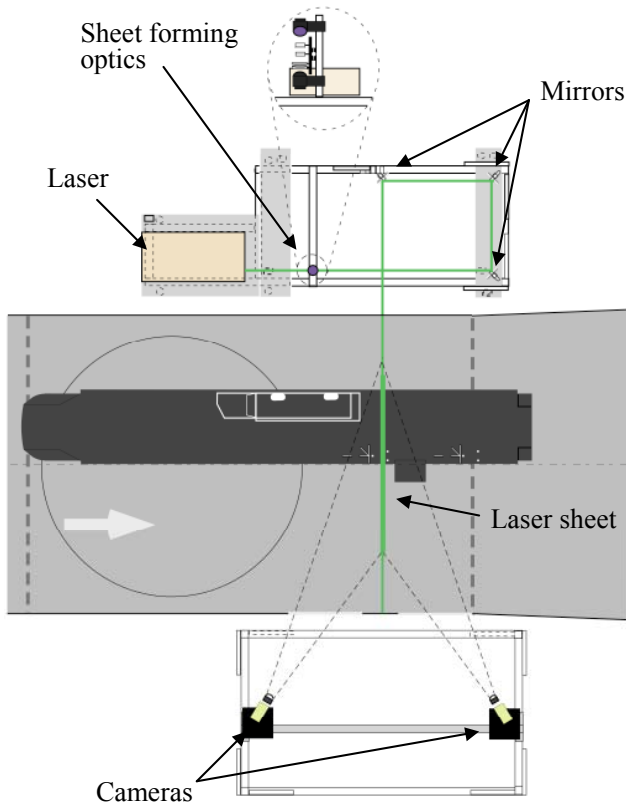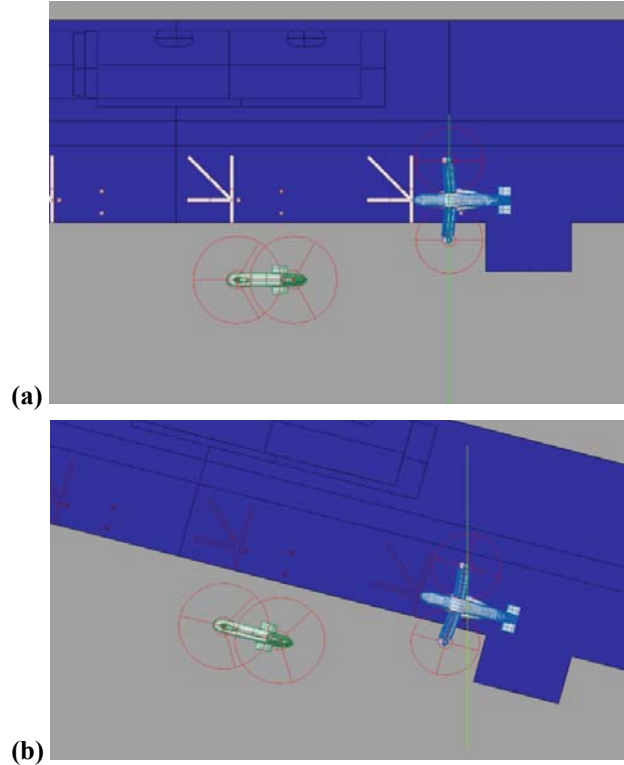

(a)

(b)

Figure 9. PIV survey plane orientation relative to ship at (a) 0° yaw and (b) 15° yaw

Figure 8. PIV system setup

TEST PLAN & EXECUTION

The test was divided into four major phases as described in Table 2. The intent was to conduct the test in a logical build-up fashion in order to quantify the individual, uncoupled contributions of each player before proceeding to the fully coupled ROD scenario. The actual sequence of execution was determined by the timetable of model hardware delivery. Hence, Phase II was completed first, followed by a very abbreviated Phase I, and then Phase III and IV.

Defining the test conditions in terms of operational parameters made the test matrix tractable. WOD were limited to 20 to 45 knots full-scale at azimuths of 000 and 345 degrees. Position of the on-deck V-22 was limited to Spots 7 and 8, the two aft portside spots currently designated for V-22 operations on the LHA. Likewise, the myriad of possible positions of the upwind aircraft relative to the on-deck V-22 was delineated by mission representative approach parameters. Thus, as shown in Figure 10, longitudinal separation was defined by landing spot separation distances, aircraft height by mission representative wheel-height-over-deck (WHOD), and lateral offset in terms of multiples of half the V-22 rotor-center-to-rotor-center distance, b/2.

Table 2. Description of Major Test Phases

Phase	Configuration	Objectives
I.	Isolated Upwind A/C (V-22, CH-46, CH-53E)	PIV measurement velocity field at various rotor diameters downwind of A/C for various advance ratios and thrust levels
II.	LHA alone	PIV measurement of velocity field at port-side deck spot for prescribed WOD conditions
III.	LHA + on-deck V-22 + upwind A/C	Force and Moment data of on-deck V-22 for prescribed WOD and upwind A/C positions
IV.	LHA + on-deck V-22 + upwind A/C	PIV measurements of flowfield at V-22 deck spots 7 & 8 for critical WOD and upwind A/C position combinations identified in Phase III
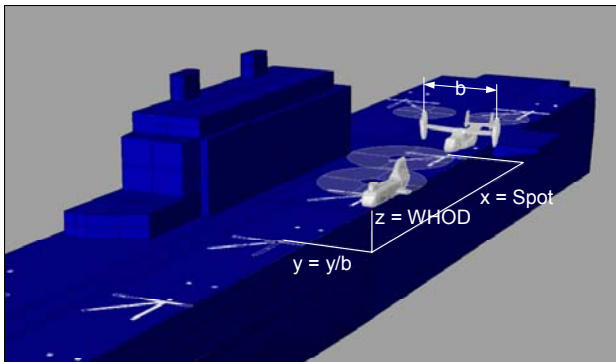
Figure 10. Upwind A/C approach parameters

RESULTS

The following sections describe the testing procedure and representative results for each test Phase in the order executed. For relevance sake, test conditions and results are often referred to in terms of their full-scale equivalent parameters. A more complete description of the test plan, facility, models, measurements, and results is found in [1].

Phase II: Ship Alone

This phase concentrated on characterizing and quantifying the ship airwake at each of the portside deck spots from which the V-22 might operate. PIV measurements were acquired at Spots 2, 4, 7, and 8 (masking of the laser light sheet by the ship island

precluded Spots 5 and 6), at full-scale equivalent winds of 10, 20, 30 and 40 knots at azimuths of 000, 355, 350, and 345 degrees. Figure 11 shows the relative position of the PIV cross-flow survey planes for ship airwake measurement. Figure 12 shows a composite of the PIV measurements taken at conditions simulating a WOD of 000 deg. at 40 knots.
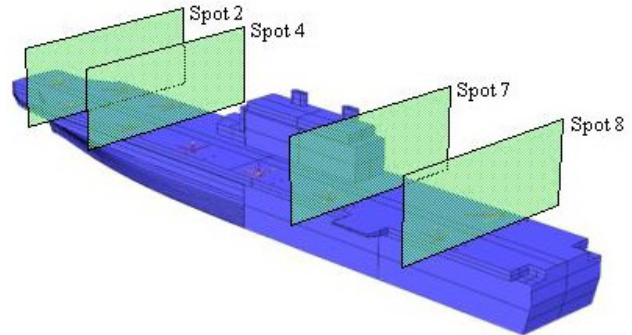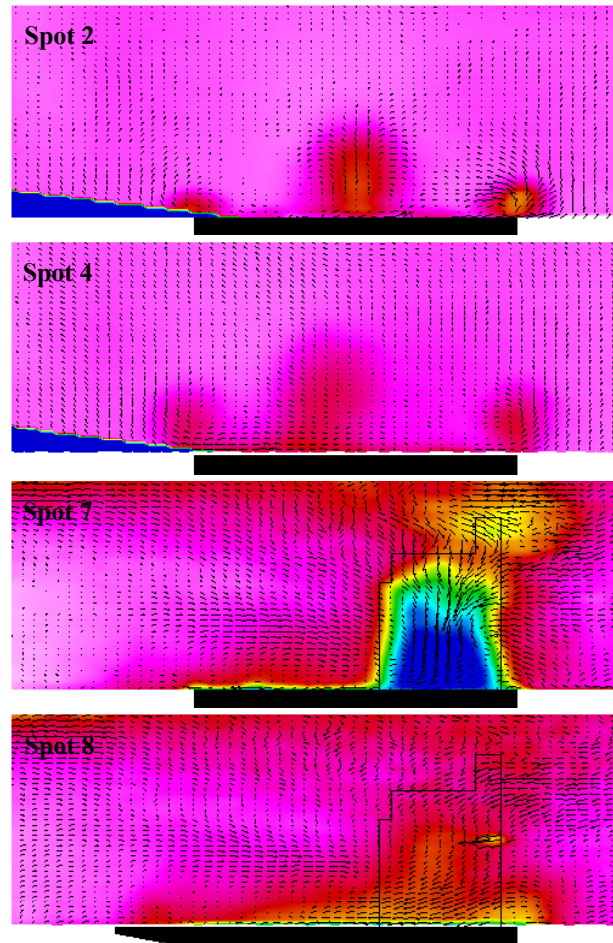

Figure 11. PIV survey planes for ship airwake

Figure 12. PIV measurements of ship airwake for WOD 000° at 40 kts

Velocities in the freestream direction are represented by the color contours while in-plane velocities are shown as vectors (for clarity sake only 25% of the available vectors are shown). The reverse flow region in the wake of the island is clearly evident at Spot 7. Deck edge vortices apparent at the forward Spots 2 and 4 appear to dissipate by the time they reach Spots 7 and 8. Figure 13 shows the same composite for WOD azimuth of 345 deg.
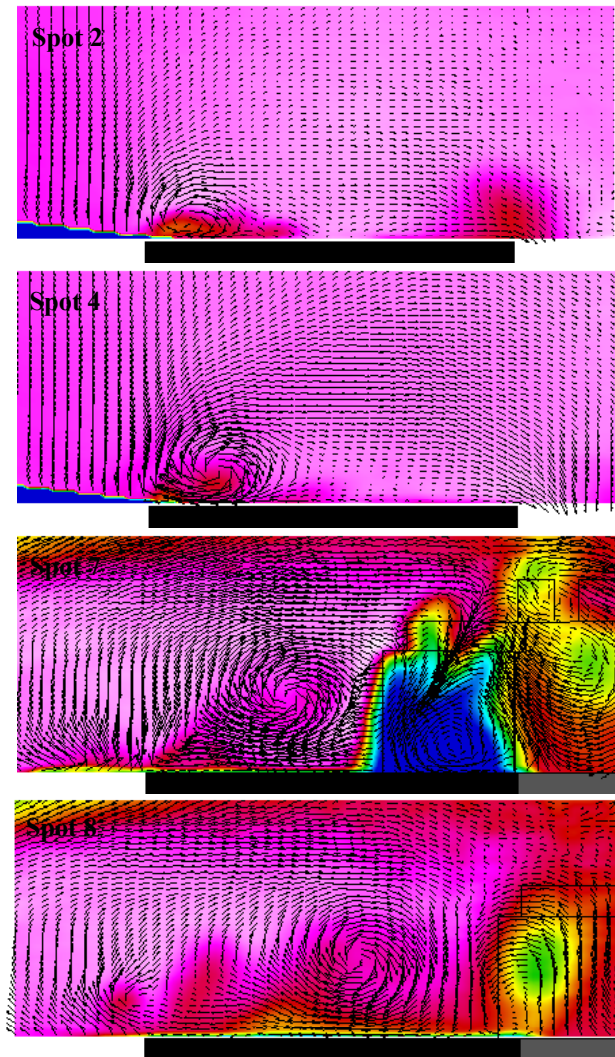

Figure 13. PIV measurements of ship airwake for WOD 345° at 40 kts

As can be seen, the character of the airwake changes considerably with 15 deg. of yaw. At 345 deg., a prominent vortical region emanating from the gun-port cutout region near the bow can be traced as it grows in cross-section all the way back to Spot 8. Also evident at Spots 7 and 8 is a strong upwash region along the port deck edge that has a significant influence on the ROD interaction. Figure 14 compares the scaled mean vertical velocity profiles at Spots 7 and 8 at a height above deck corresponding to the plane of the on-deck V-22 rotors.

In addition to PIV, limited surface oil flow visualizations were obtained using a mixture of motor oil, olive oil, mineral spirits, and titanium dioxide. Figure 15 shows the pattern established after running at approximately 36 ft/sec at 15 deg. yaw for 20 minutes. A stagnation line stretching from bow to stern appears to match the trajectory of the vortex seen in the PIV planes of Figure 13.
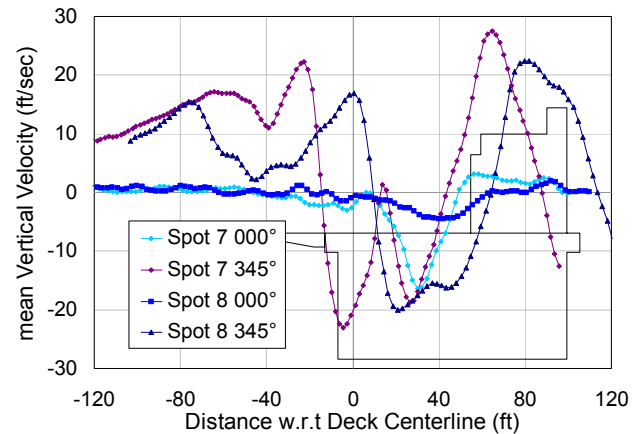

Figure 14. Scaled mean vertical velocity profiles at Spots 7 and 8, WOD 40 kts

Figure 15. Surface oil flow visualization for WOD 345°

Phase I: Isolated V-22

The intent of this phase was to characterize and quantify the wake of the upwind aircraft in isolation at downwind distances comparable to the scaled landing spot separation distances. Delays in the delivery of aircraft model hardware and the higher priority given to Phases III and IV combined to severely limit Phase I. A brief opportunity for acquiring PIV data behind an isolated V-22 model presented itself at a time when the tunnel drive system was undergoing maintenance. Six large fans were placed in the diffuser of the tunnel, producing a maximum test section speed of 12 ft/sec (equivalent to approximately 21 knots full-scale). At these less than ideal conditions PIV measurements were made at three locations downstream from the V-22 operating at two different thrust coefficients. Figure 16 shows one such PIV image taken approximately 2 rotor diameters downstream of the V-22 powered model operating at a CT of 0.0105 and an advance ratio of 0.044. The color contours represent the mean freestream velocity and the vectors represent the in-plane velocity components.
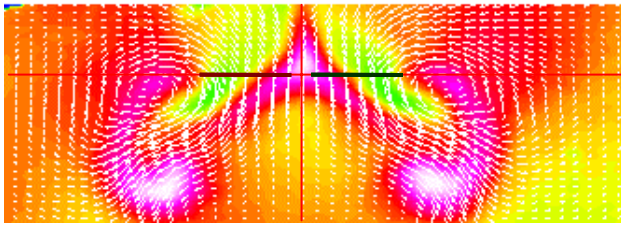

Figure 16. PIV measurement of isolated V-22 wake

Phase III: Ship + On-deck V-22 + Upwind CH-46/CH-53E

The majority of the test concentrated on measuring the on-deck V-22 response to a wide range of upwind CH-46 positions. Only a limited amount of data was acquired with the CH-53E as the upwind aircraft, and no data with an upwind V-22 due to tunnel time constraints. Priority was given to using the CH-46 as the upwind aircraft since both documented ROD events during Developmental Testing of the V-22 occurred while recovering a CH-46 to an upwind spot. Figure 17 shows the test setup for replicating one such event with the on-deck V-22 positioned at Spot 7 and the upwind CH-46 above Spot 4.

All Phase III testing followed the same general procedure: with wind-off, the on-deck V-22 was set to an initial low thrust level (CT=0.0008) predicted for a ground turning V-22 under static conditions with its thrust control lever (TCL) at its aft stop. Differential collective pitch was introduced to trim out rolling moment to the extent allowed by the control system. With the upwind aircraft positioned "up and away" (the traverse extreme upper left limit, looking upstream) and rotors stationary, the tunnel was

brought up to the desired speed without any adjustment to the on-deck V-22 trim. This state provided a wind-on reference condition for all subsequent interaction test points. The upwind aircraft was then brought up to speed and trimmed to the desired thrust and traversed through a preprogrammed array of positions defined by scaled spot separation, lateral offset, and WHOD. At each position, the upwind aircraft was re-trimmed as necessary before taking data, while the on-deck V-22 was operated "hands-off". Using this procedure, the forces and moments of the on-deck tiltrotor were mapped as a function of upwind aircraft position.
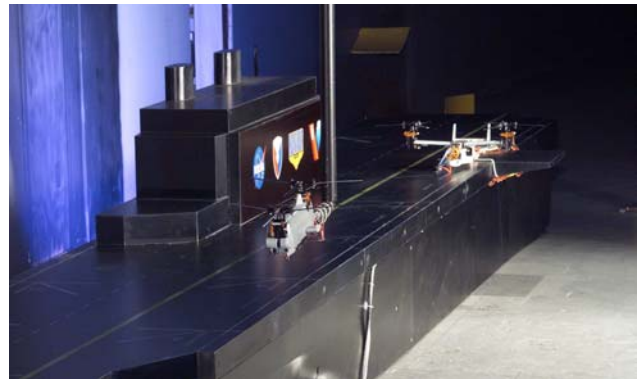

Figure 17. Phase III test set-up

In all, force and moment data were acquired for more than two hundred combinations of WOD, on-deck V-22 spot, and upwind CH-46 positions facilitating sensitivity studies of the effects of WOD speed, WOD azimuth, longitudinal separation, lateral offset, and WHOD on the on-deck V-22 roll response. Representative results are presented in terms of a "referred rolling moment" parameter, defined as follows:

$$\overline{RM} = \frac{(RM - RM_{ref}) \cdot 995328}{RM_o}$$

where:

- $RM \equiv$ measured rolling moment (ft-lbs, + right wing down)
- $RM_{ref} \equiv$ rolling moment measured at V-22 wind-on reference point (with upwind a/c positioned "up and away" and rotors stopped)
- $995328 \equiv$ moment scaling factor ($= 483 \cdot 32$)
- $RM_o \equiv$ the full-scale rolling moment estimated to be sufficient to cause a 43,000 lb V-22 to lift a main gear (6.2 deg. roll)

Figure 18 shows the on-deck V-22 rolling moment response to upwind CH-46 position (longitudinal separation in terms of deck spots, lateral offset in terms of V-22 wingspans, constant full-scale WHOD of 20 ft) for a simulated full-scale WOD condition of 345 deg. at 35
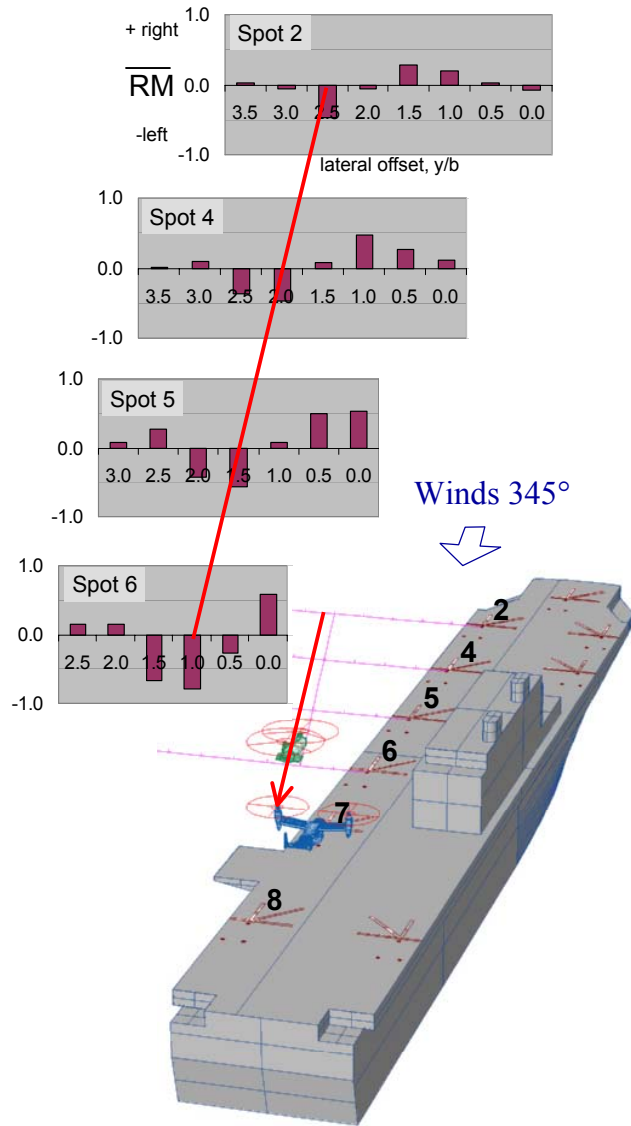
Figure 18. V-22 rolling moment response to upwind CH-46 position, WOD 345° at 35 kts

knots. Note that the locus of maximum left roll response, shown in both the schematic and the bar charts, lies on a direct windward line between the CH-46 and the on-deck V-22 left rotor.

Figure 19 illustrates the impact of the ship airwake on the ROD interaction. Shown is the on-deck V-22 rolling moment response with WHOD of an upwind CH-46 for two distinct WOD conditions: 35 knots at 000 deg. and 345 deg.. Both height sweeps were conducted with the CH-46 at Spot 6 and a lateral offset of 2b/2, the position corresponding to the maximum left roll interaction in Figure 18. The trend for winds straight down the deck is the expected one, namely that rolling moment would increase with WHOD to a maximum, corresponding to the height at which direct impingement of the CH-46 wake

occurs, then decrease as further increases in WHOD raise the wake of the CH-46 above the plane of the V-22 rotors. The trend for winds 15 degrees to port is of a different character. Here, the interaction is strongest at low WHOD and decreases with increasing wheel height of the upwind CH-46. This unexpected trend is indicative of the significant role the ship airwake can play in ROD interactions, a role more clearly revealed by PIV measurements in Phase IV.
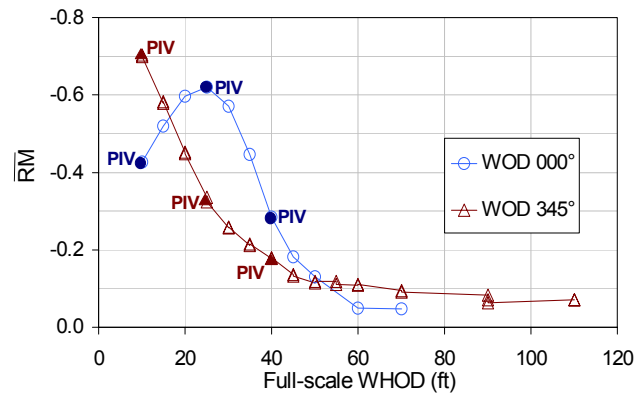

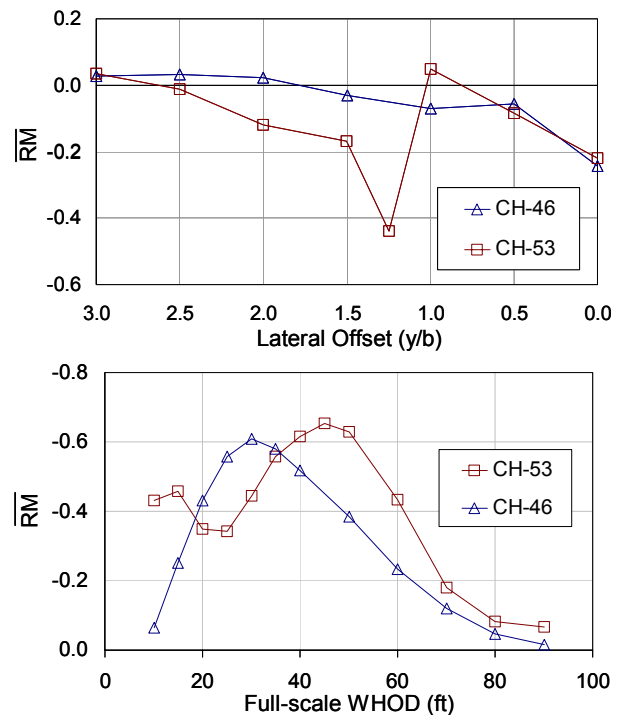**Figure 19. V-22 rolling moment response vs. upwind CH-46 WHOD**

Figure 20. V-22 rolling moment response vs. (a) lateral offset and (b) WHOD of the CH-53E and CH-46 aircraft

Limited interaction data were acquired for a full-scale WOD of 000 deg. at 35 knots with the CH-53E as upwind aircraft and the on-deck V-22 at Spot 8. Figure 20 compares the on-deck V-22 rolling moment response for lateral offset and WHOD sweeps of the CH-53E and CH-46 upwind aircraft. As expected, the stronger downwash of the heavier CH-53E results in a stronger interaction with the on-deck V-22. At a given wind speed, the wake of the CH-53E is less skewed than that of the CH-46, thus the maximum interaction occurs at a higher WHOD. Further investigation of the interactions of the on-deck V-22 with an upwind CH-53E and V-22 aircraft was resumed in a second wind tunnel entry (concluded in November 2003); the results of which will be documented in a subsequent report.

Phase IV: Ship + Upwind CH-46 with PIV

The objective of this phase was to acquire complementary PIV measurements of the flow field at V-22 designated deck Spots 7 and 8 for the sensitivity studies and the critical WOD and upwind A/C position combinations identified in Phase III. For the majority of testing in this phase the on-deck V-22 was replaced (or left inoperative at a downstream spot) by the PIV light sheet in an attempt to quantify the flowfield disturbance "seen" by the V-22 rotors. Ancillary PIV measurements were made at one rotor diameter ahead of the operating on-deck V-22 to check the assumption of superposition, i.e. that little coupling exists between the wake of the V-22 rotors and the flowfield disturbance.

To illustrate the insights provided by the PIV measurements, we return to the V-22 rolling moment vs. WHOD sensitivity study presented in Figure 19. Three points were selected from each WHOD sweep for further investigation with PIV. Figure 21 presents a composite of the PIV measurements acquired for WOD 000 deg. at 35 knots. Each PIV image represents an average of 100 realizations of the flow field looking upstream consistent with the image area shown in the top frame. As before, velocities in the freestream direction are mapped as color contours while the in-plane velocities are shown as vectors. Place keepers for the ship deck (black rectangle lower right), on-deck V-22 left and right rotors (red and green line, respectively), and CH-46 aft rotor (blue line) are included in each image.

For the current scenario, the PIV plane is approximately 1.8 rotor diameters downstream of the CH-46 aft rotor center. At this distance, the individual tip vortices of the fore and aft rotors have rolled-up into two "super-vortices", making the tandem helicopter wake resemble that of a fixed wing aircraft. Recall that the WHOD sweep was performed at the lateral offset resulting in a peak left rolling moment for the on-deck V-22. As
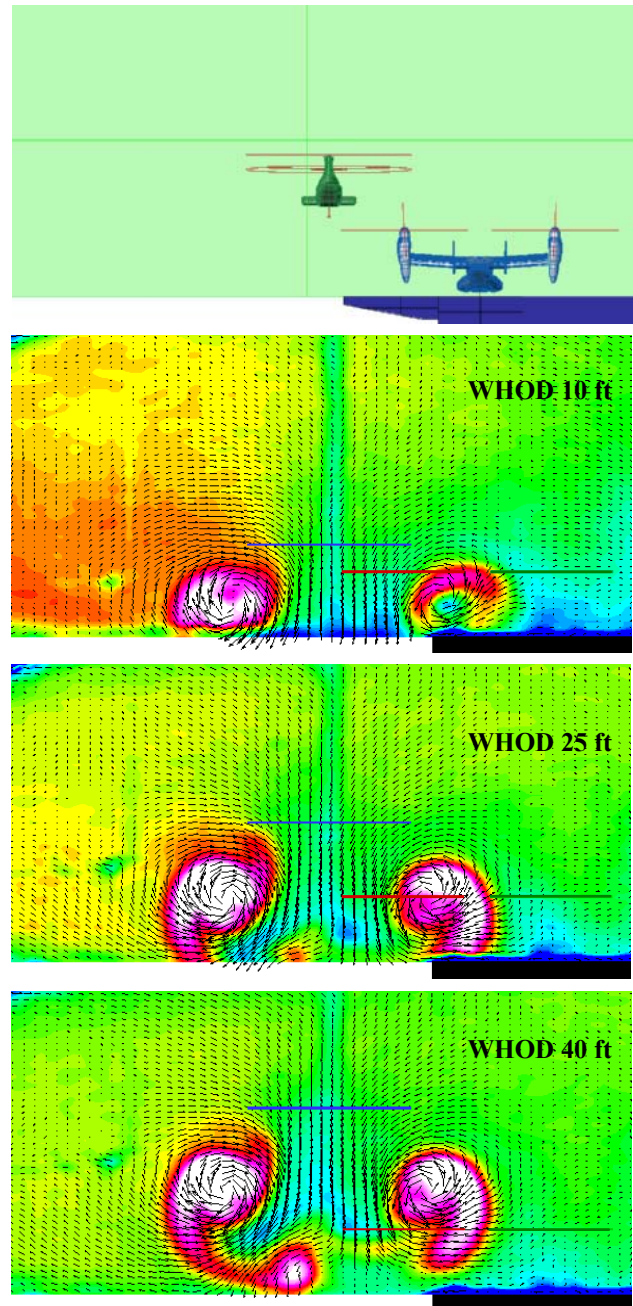

Figure 21. PIV measurements at Spot 7 with CH-46 at Spot 6 for WOD 000° at 35 knots

shown in the PIV images, this lateral offset results in the on-deck V-22 left rotor being immersed in the downwash of the upwind aircraft while its right rotor is in the upwash field. The resulting thrust reduction on the left rotor and the thrust increase on the right rotor give rise to the negative roll experienced by the on-deck V-22. The trend in rolling moment magnitude with increasing WHOD evident in Figure 19 is clearly explained by the PIV sequence. The peak rolling moment at a WHOD of 25 ft corresponds with a direct impingement of the upwind
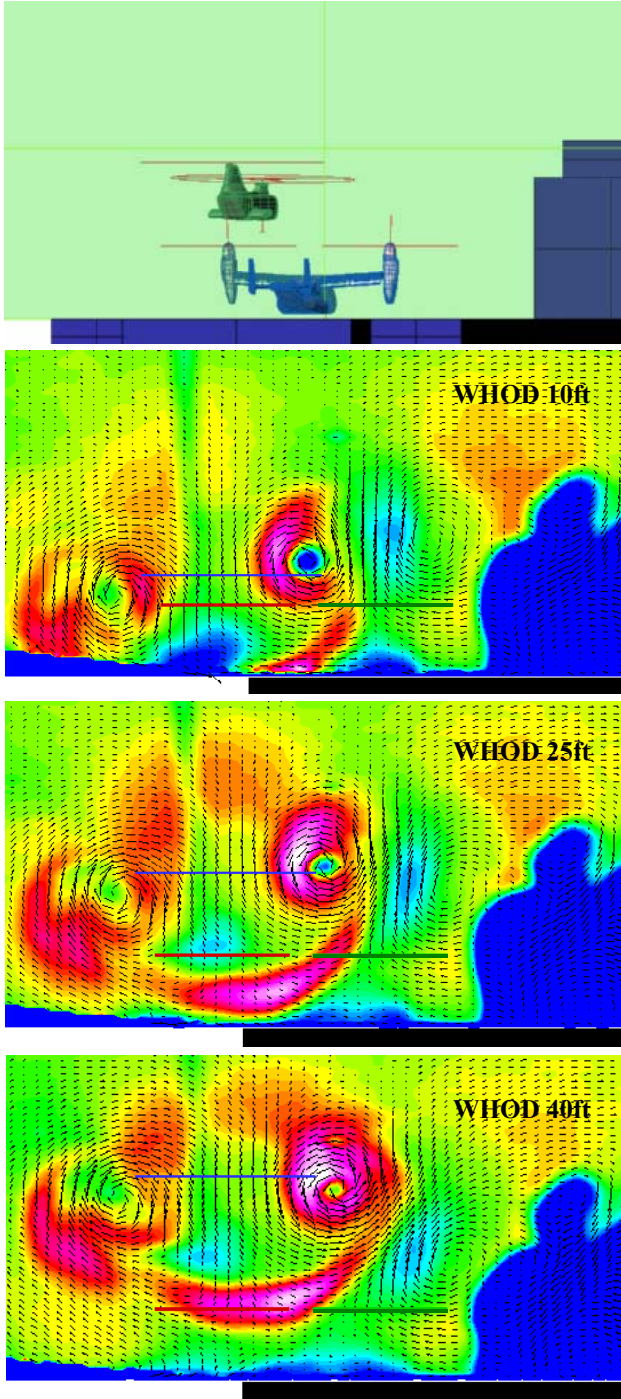
Figure 22. PIV measurements at Spot 7 with CH-46 at Spot 6 for WOD 345° at 35 knots

aircraft wake on the on-deck V-22 rotor disk plane. The lower rolling moment magnitudes at WHOD at 10 ft and 40 ft result from the upwind aircraft wake passing below and above the V-22 rotor disk plane respectively.

Figure 22 presents a similar composite of PIV measurements acquired for WOD 345 deg. at 35 knots.

Here the influence of the upwash field generated under portside wind conditions is clearly evident. The effect of the ship airwake is to lift the wake of the upwind aircraft into the plane of the on-deck V-22 rotors, thus accounting for the peak rolling moment occurring at a low WHOD.

The PIV sequence shows that the upwind aircraft wake passes increasingly above the plane of the V-22 rotors with further increases in WHOD.

Apart from facilitating qualitative observations of the flowfield, the PIV measurements quantify the flowfield disturbance. Figure 23 presents scaled downwash profiles extracted from the PIV data. These profiles have been superimposed as a non-uniform inflow in analytical models of the V-22 rotors for predicting the thrust asymmetry that would result on a full-scale on-deck V-22.
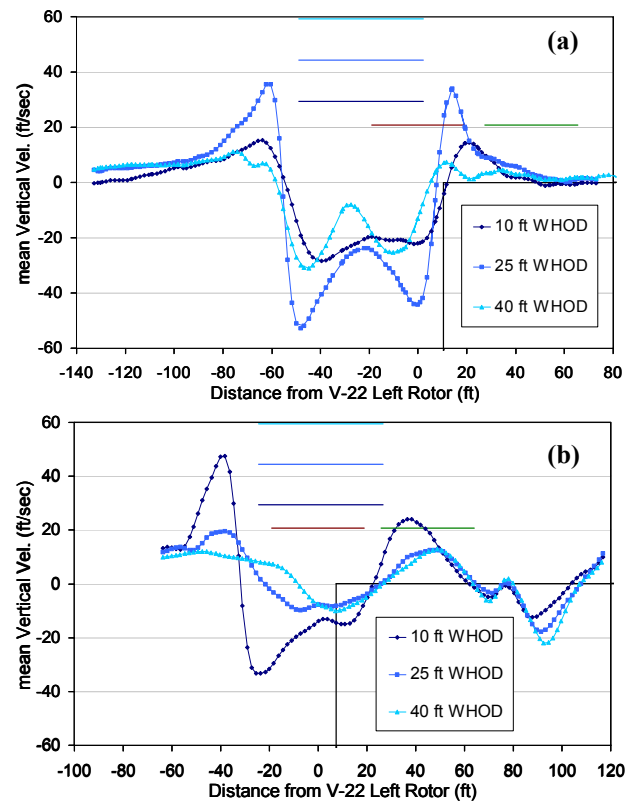

Figure 23. Scaled mean downwash profiles extracted from PIV data for WOD of 35 kts at (a) 000° and (b) 345°

The validity of the superposition assumption is supported by Figure 24 which presents the scaled mean downwash and outwash profiles extracted from PIV measurements one rotor diameter ahead of the on-deck V-22 rotors, with and without the V-22 rotors turning at 100% Nr. Comparing the profiles shows that, at the low thrust levels typical of a ground turning V-22, the on-deck V-22 imparts very little influence on either the isolated ship
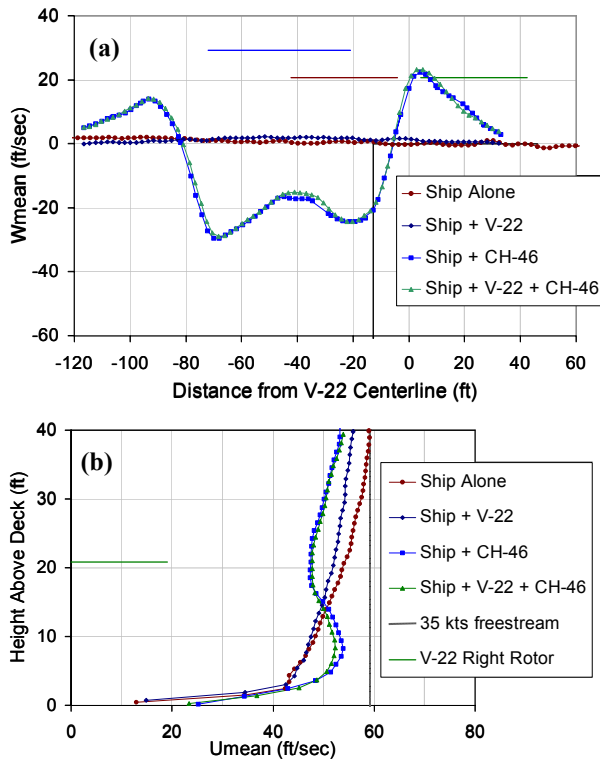
Figure 24. Scaled mean (a) downwash and (b) outwash profiles extracted from PIV measurements one rotor diameter ahead of the on-deck V-22 at Spot 8

airwake (Ship + V-22 vs. Ship alone) or the combined ship airwake and upwind CH-46 wake (Ship + CH-46 + V-22 vs. Ship + CH-46) flowfields.

CONCLUDING REMARKS

The V-22 "Roll On-Deck" scenario was the subject of a small-scale wind tunnel investigation. The results of the investigation have provided significant insights into the key interactional aerodynamic phenomena that drive the on-deck V-22 uncommanded roll response. The combination of airframe force and moment and detailed velocity field measurements has allowed the interaction to be characterized and quantified, and, most importantly, bound through the identification of critical scenarios.

Small-scale wind tunnel testing continues to offer an expedient and low-risk means of investigating full-scale aeromechanics phenomena. Results and observations from the present test are consistent with recorded full-scale events and have been used to guide the planning and reduce the risk of full-scale shipboard interactional testing of the V-22.

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